DISCUSSION AND SOLUTION OF THE TRAJECTORY CURVE OF UPWARD EJECTION SEATS EJECTED FROM HIGH SPEED AIRCRAFT

By

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OF UPWARD EJECTION SEATS EJECTED FROM
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PREFACE

The emergency escape by means of an ejection seat from high speed aircraft has become a source of numerous problems. One of the problems is the accurate prediction of the path of the seat immediately upon leaving the airplane, better known as the trajectory path.

Before arriving at the solution for such a curve, it is necessary to study carefully all dynamic effects acting on the seat and its subject. The purpose of this study is to present the conclusions made from an investigation of several flight tests on ejection seats, to evaluate previously determined methods of calculating the trajectory curve, and to present a modified and simplified method of predicting an accurate trajectory.

Indebtedness is acknowledged to Professor L. A. Fila for his technical assistance and guidance during the study, Mr. Alton P. Juhlin for his assistance in procuring certain documents, and to the following for supplying the documents and material used during the study: Douglas Aircraft Company, Inc., Santa Monica and Tulsa Divisions; Stanley Aviation Corporation, Denver, Colorado; and the United States Air Force Air University Library, Maxwell Air Force Base, Alabama.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

NOMENCLATURE

U_o = Relative wind velocity at time of ejection - ft/sec.

U_x = Relative wind velocity at any time t - ft/sec.

V_x = Relative seat velocity in the horizontal direction at any time t - ft/sec.

V_y = Relative seat velocity in the vertical direction at any time t - ft/sec.

t = Time in seconds.

x = Displacement in the horizontal direction - ft.

y = Displacement in the vertical direction - ft.

D = Aerodynamic drag - lb.

L = Aerodynamic lift - lb.

M = Aerodynamic moment - ft.-lb.

W = Total ejected weight of seat, man, and equipment - lb.

g = Gravitational constant - 32.2 ft/sec^2.

m = $\frac{W}{g}$ Mass - slugs.

C_D = Coefficient of drag - dimensionless.

C_L = Coefficient of lift - dimensionless.

S = Projected frontal area of seat - sq. ft.

ρ = Atmospheric density - slugs/ft^3.

β = Angle of ejection with the vertical - degrees.

α = Angle of attack of the seat - degrees.

C.G. = Center of gravity of total ejected mass.

The subscript o denotes initial or starting condition.

PART I.

INTRODUCTION

For the past ten years extensive flight tests have been made proving the adequacy of the ejection seat as means of escape from high speed aircraft. Although these tests have not been made with the intention of comparing theoretical trajectories with the actual trajectories, the recorded test data is available for this comparison. With the improvement of recording apparatus and also with improved photography, it soon became evident that actual trajectories were not as predicted.

Upon further investigation it became evident that the effects of certain dynamic forces and the effects of variation of other dynamic forces were overlooked in the theoretical calculations.

To set up an equation to describe the trajectory which would include all possible variables would prove to be a laborious task. If such an equation was to be developed, it is doubtful that anything short of an electronic calculator could solve it in a reasonable amount of time. Many methods of calculation have been suggested which eliminate certain of these variable forces but due to the variation of these forces, the majority of these methods are restricted to a very short range of flight speeds.

The intention of this study is to discuss all the dynamic forces which could effect the trajectory and to arrive at a method by which these dynamic forces and their variations may be incorporated into a solution of the trajectory curve.

PART II.

CONTRIBUTING FORCES

The following figure is a brief sketch of an upward ejection seat during its trajectory with the various forces which contribute to its motion.

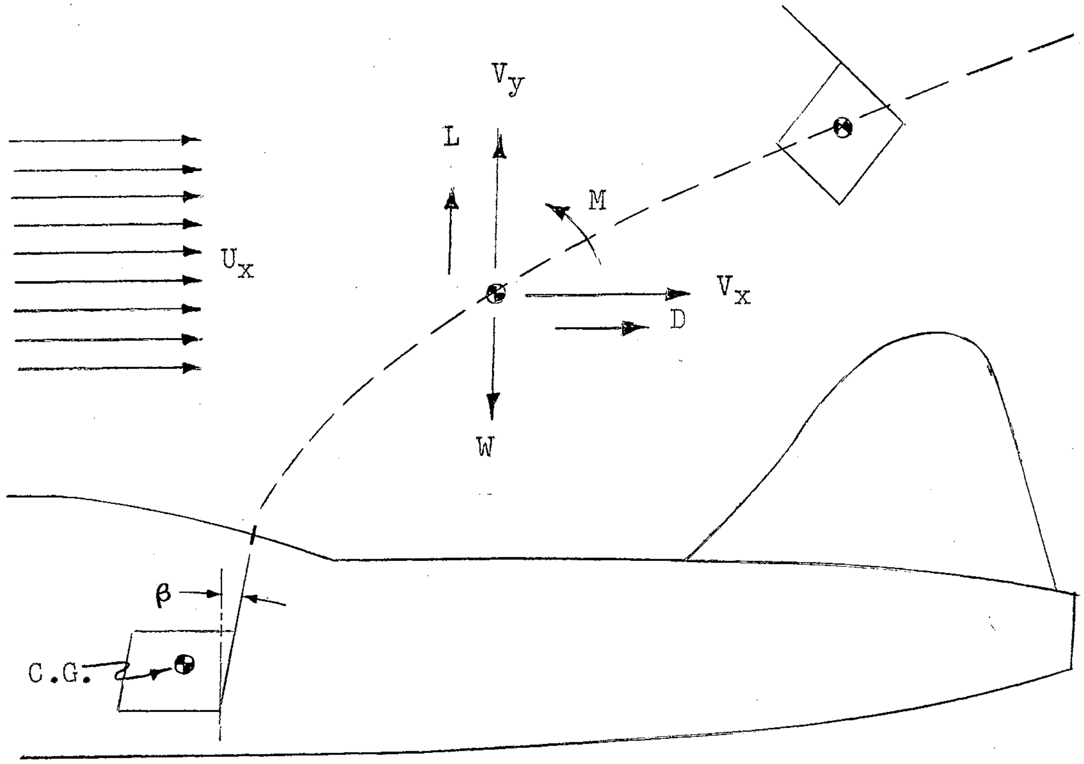

Figure No. 1

Throughout this report it will be assumed that the configuration of the seat is known. This would include such criteria as: seat dimensions, total ejected weight, ejection angle, terminal velocity of the catapult, and location of the center of gravity. The effect of the variation of these criteria on the trajectory is, of course, of interest to the designer who can find extensive discussion of the variations in the appended references of this report.

Although it is not the intent of this report to discuss the variation of such quantities, it is expedient to call attention to one particular quantity; the terminal velocity of the catapult. There are some factors of operation which cannot be controlled in the design of an otherwise reliable and adequate catapult such as the ballistic catapult produced by Frankfort Arsenal.[1] A specific catapult is designed to impart a certain velocity to a given mass at the end of its power stroke under standard conditions and numerous tests are performed to substantiate the design. In applying the catapult to an ejection seat it has been found that the terminal velocities do vary, sometimes appreciably from the designed velocity. There are several causes for these variations: atmospheric conditions, changes in ejected weight, excessive friction during guided stroke and lurching of the airplane during the power stroke of the catapult. There is another one, however, which is seldom considered and which probably has a considerable effect. This one is the elastic property of the ejection seat and its component parts. The effect of these elastic properties are covered in detail in Reference No. 2. Briefly, the entire ejection system and supporting aircraft structure is considered as an elastic, damped vibrating system during ejection.

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[1] Design and functional information on such catapults is included in the Frankfort Arsenal Engineering Manual On Cartridge Actuated Devices.

Attempts have been made to consider certain adverse maneuvers of the airplane during ejection when calculating the trajectory curve. Such maneuvers would include up, down, and sideward lurching, acceleration, deceleration, "g" forces due to pull-outs and locked controls, and even upside-down ejections. Evaluation of the effects of such conditions is beyond the scope of this report. Actually, the references contain no information of value on this subject although it only seems reasonable that tests have been performed to evaluate such flight conditions. It seems reasonable that such flight conditions should definitely be considered, not particularly with the intent of including them in a trajectory calculation but rather from an operational and design standpoint.

The mention of structural elasticity and adverse maneuvers is made as a possible explanation for the discrepancy between theoretical and actual trajectories. The effects of these two factors are not considered in this work but they can be considered for future development.

The aerodynamic forces to be considered consist of drag, lift, and moment as shown in Figure No. 1. These forces vary significantly with the angle of attack and with the relative velocity of the seat in the airstream.

PART III.

SEAT ROTATION AND ITS EFFECTS ON THE AERODYNAMIC FORCES

It is emphasized that the seat is defined as the standard shaped seat structure with standard ejection equipment and the occupant who is attached to it. Additional equipment would naturally alter the dynamics of the seat in the airstream.

The majority of the reports reviewed during this study indicate that the seat will rotate in a forward direction; that is, head over feet in a counter-clockwise sense as viewed from the left.[1] The causes for this type of rotation arise from the normal eccentricity of the catapult thrust in relation to the center of gravity and from the characteristic aerodynamic moment acting on the seat about the center of gravity. References No. 3 and No. 13, on the other hand, indicate a slightly different movement. The photographs included in these reports show the seat to rotate forward to approximately 30°. It then begins rotation in the opposite direction. In the first of these two reports the movement may be attributed to a drag chute apparatus attached to the head rest. This movement in the second report is ascribed to the seat configuration; that is, the seat is so designed that the combined C.G. of the seat and man is so located as to cause the aerodynamic moment to

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[1] Photographs showing this type of rotation are clearly shown in References No. 7, No. 8, No. 9, No. 10, No. 11, and No. 12.

counteract the catapult moment after a certain amount of travel has taken place. Of course, the aerodynamic moment on a body is strongly influenced by the location of the C.G. within the body. Reference No. 1 discusses in detail the various causes of seat rotation and the effects on seat stability due to change of C.G. and addition of stabilizers.

Drag and lift forces may be expressed in the two following familiar equations:

$$D = C_D \tfrac{1}{2} \rho U_x^2 S$$

$$L = C_L \tfrac{1}{2} \rho U_x^2 S$$

The variables are C_D, C_L, and velocity. The velocity depends on the drag force and in turn, at high velocities, the drag coefficient depends on the velocity. Because there is no analytic relationship between the drag coefficient and the velocity, the analytical solution of the trajectory becomes indeterminate.

Nevertheless, C_D and C_L can be expressed in terms of the Mach number and seat angle of attack from experimental data. This relationship is represented in Figures No. 4 through No. 13.[2] The solution of the trajectory must be accomplished through the medium of these graphs

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[2] Taken from Massachusetts Institute of Technology Wind Tunnel Report #69.

PART IV.

PREVIOUSLY DEVELOPED METHODS OF TRAJECTORY CALCULATIONS

The following documents which contain methods of calculating trajectories were reviewed: References No. 3, No. 4, No. 5, and No. 6. In addition to these, reports from Douglas Aircraft Company, Santa Monica, California and Stanley Aviation Corporation, Denver, Colorado were studied. The majority of these reports are rather mathematically involved but in their entirety are correct solutions for the problem they set out to solve.

The Douglas Aircraft Company derived an equation of motion which involved all of the possible variations in dynamic forces. Because of its complex nature, the equation was modified for programming on a Reeves Analogue Computer. One advantage of this type of computer is the ease by which the various constants and initial conditions can be changed, one at a time, and the resulting effect on the trajectory studied. Results obtained by this method were compared with actual sled test data and a very close agreement was found. In fact, of all the reports which were reviewed, the Douglas method had the best correlation between theoretical and actual trajectories.

Reference No. 5 suggests a step-by-step integration method. Although this method did not consider all of the variables, it offers a logical procedure to approach the problem.

In summarizing the entire group of reports which have been studied, it appears that the two methods mentioned above are the more reliable solutions to our problem. The computer method is the more accurate of the two. This method, of course, requires much preparation and the availability of an electronic computer. The step-by-step integration method is by far the more practical and may be used by any person familiar with the trajectory problem. This report presents a procedure for the computation of the trajectory by extending the step-by-step integration to include all the important variables.

PART V.

PROPOSED NUMERICAL INTEGRATION METHOD FOR UPWARD EJECTION SEAT TRAJECTORY CALCULATIONS

In order to utilize the graphs of Figures No. 4 through No. 13, the velocity and angle of attack at a specific instant must be known. The angle of attack varies as shown in Figure No. 2. Here it is related to a set of Cartesian coordinates.

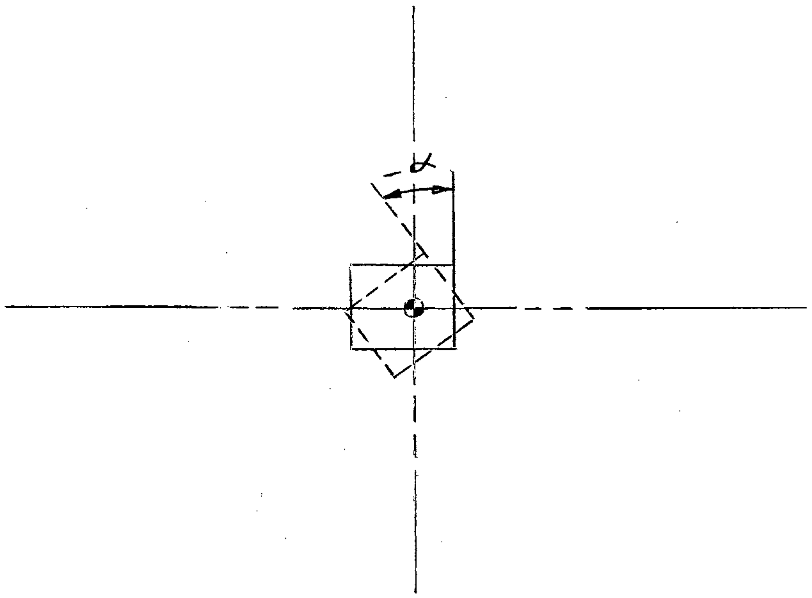

Figure No. 2

It is necessary to have a reasonably good approximation of the relative velocity U at any time t. For this purpose the following derivation is made.

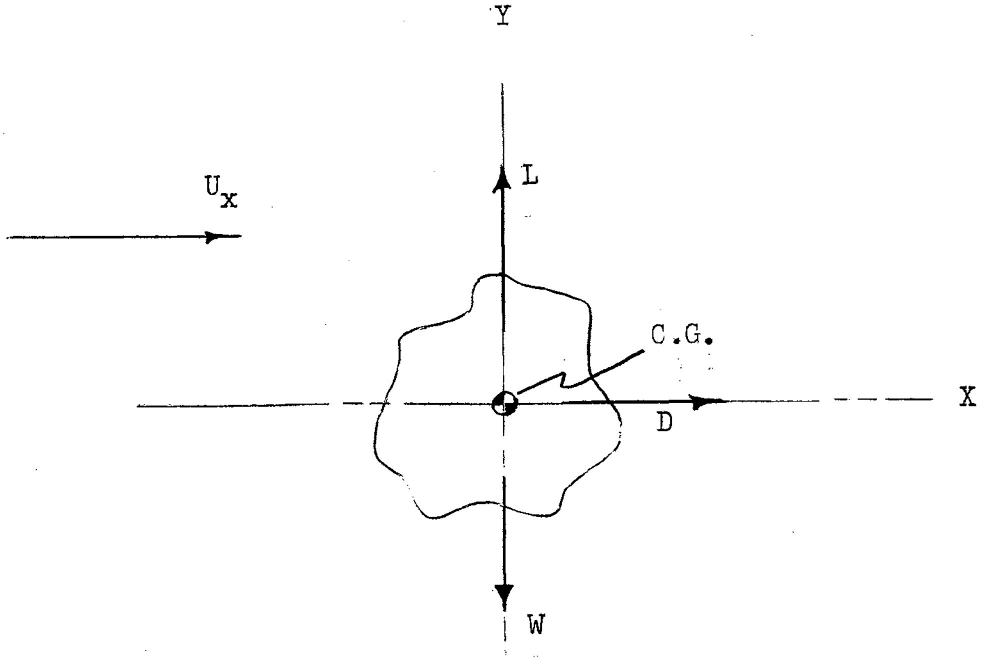

Figure No. 3

Figure No. 3 represents the components of forces which act on an ejection seat at the termination of the catapult stroke. The trajectory curve has its origin at the point of separation from the catapult.

The drag and lift forces are assumed to vary as the square of the velocity; thus:

$$D = D_o \left(\frac{U_x}{U_{xo}}\right)^2 \quad \text{------------} \quad (1)$$

and

$$L = L_o \left(\frac{U_x}{U_{xo}}\right)^2 \quad \text{------------} \quad (2)$$

Basic equilibrium equation in the horizontal direction (x direction):

$$\frac{W}{g} \ddot{x} + \frac{D_o}{U_{xo}^2} (\dot{x})^2 = 0 \quad \text{---------} \quad (3)$$

$$m\ddot{x} + \frac{D_o}{U_{xo}^2} (\dot{x})^2 = 0$$

Letting $p = \dot{x}$ and rearranging terms:

$$M \frac{dp}{dt} + \frac{D_o}{U_{xo}^2} p^2 = 0$$

$$\frac{\frac{dp}{D_o \, p^2}}{U_{xo}^2 \, m} + dt = 0$$

Let: $$\frac{D_o}{U_{xo}^2 \, m} = a$$

$$\frac{dp}{ap^2} + dt = 0$$

$$\int \frac{dp}{ap^2} + \int dt = 0$$

$$- \frac{1}{ap} + t + C = 0$$

$$- 1 + ap(t + C) = 0$$

$$p = \dot{x} = U_x = \frac{1}{a\,(t + C)}$$

at $t = 0$, $U_x = U_{xo}$

$$\therefore U_{xo} = \frac{1}{a\,C}$$

$$C = \frac{1}{a\,U_{xo}}$$

$$\therefore U_x = \frac{1}{a\,(t + \frac{1}{a\,U_{xo}})} = \frac{1}{at + \frac{1}{U_{xo}}}$$

$$U_x = \frac{U_{xo}}{\frac{D_o\,t}{U_{xo}\,m} + 1} \qquad \text{---------} \; (4)$$

Equation 4 is used to estimate the velocity at the end of each increment of time. It is observed that the initial drag force D_o appears in this equation. In computing this, it is necessary to estimate an average coefficient of drag. The method of Reference No. 6 for estimating C_D is utilized in this report. The time increments for this type of integration should be no less than .05 seconds and a total time of .5 seconds should be sufficient to show a 75 to 100 foot trajectory at velocities approaching Mach 1.

Assuming a rate of rotation, the angle of attack can be calculated at the end of each time increment. The average velocity during any time increment and the appropriate angle of attack are used to select values of C_D and C_L from the graphs. Using the C_D and C_L thus obtained, the corresponding drag and lift may be calculated. Due to the discontinuity of the drag curve in the vicinity of Mach 1, caution should be used in the interpolation of these curves in that range.

The equations for numerical integration must now be established.

$$m\ddot{x} = D$$

$$\ddot{x} = \frac{D}{m}$$

$$d\dot{x} = \frac{D}{m}\,dt$$

$$\dot{x} = \frac{D}{m}t + C$$

$$\text{at } t = 0,\ \dot{x} = V_{xo}$$

$$\dot{x} = V_x = \frac{D}{m}t + V_{xo} \quad \text{---------} \ (5)$$

$$dx = \frac{D}{m}t\,dt + V_{xo}\,dt$$

$$x = \frac{D}{2m}t^2 + V_{xo}t \quad \text{---------} \ (6)$$

$$m\ddot{y} = L - W$$

$$d\dot{y} = \left(\frac{L}{m} - g\right)dt$$

$$\dot{y} = \left(\frac{L}{m} - g\right)t + C$$

$$\text{at } t = 0,\ \dot{y} = V_{yo}$$

$$\dot{y} = V_y = \left(\frac{L}{m} - g\right)t + V_{yo} \quad \text{-------} \ (7)$$

$$dy = \left(\frac{L}{m} - g\right)t\,dt + V_{yo}\,dt$$

$$y = \frac{L}{2m}t^2 - \frac{g}{2}t^2 + V_{yo}t \quad \text{------} \ (8)$$

Equations 5 and 7 must be used to obtain starting velocities at the beginning of each time increment. Numerical integration of equations 6 and 8 will produce the x and y ordinates at time t.

The details of this method are illustrated in Part VI. in which the proposed method is compared with experimental trajectories.

DRAG COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH .6

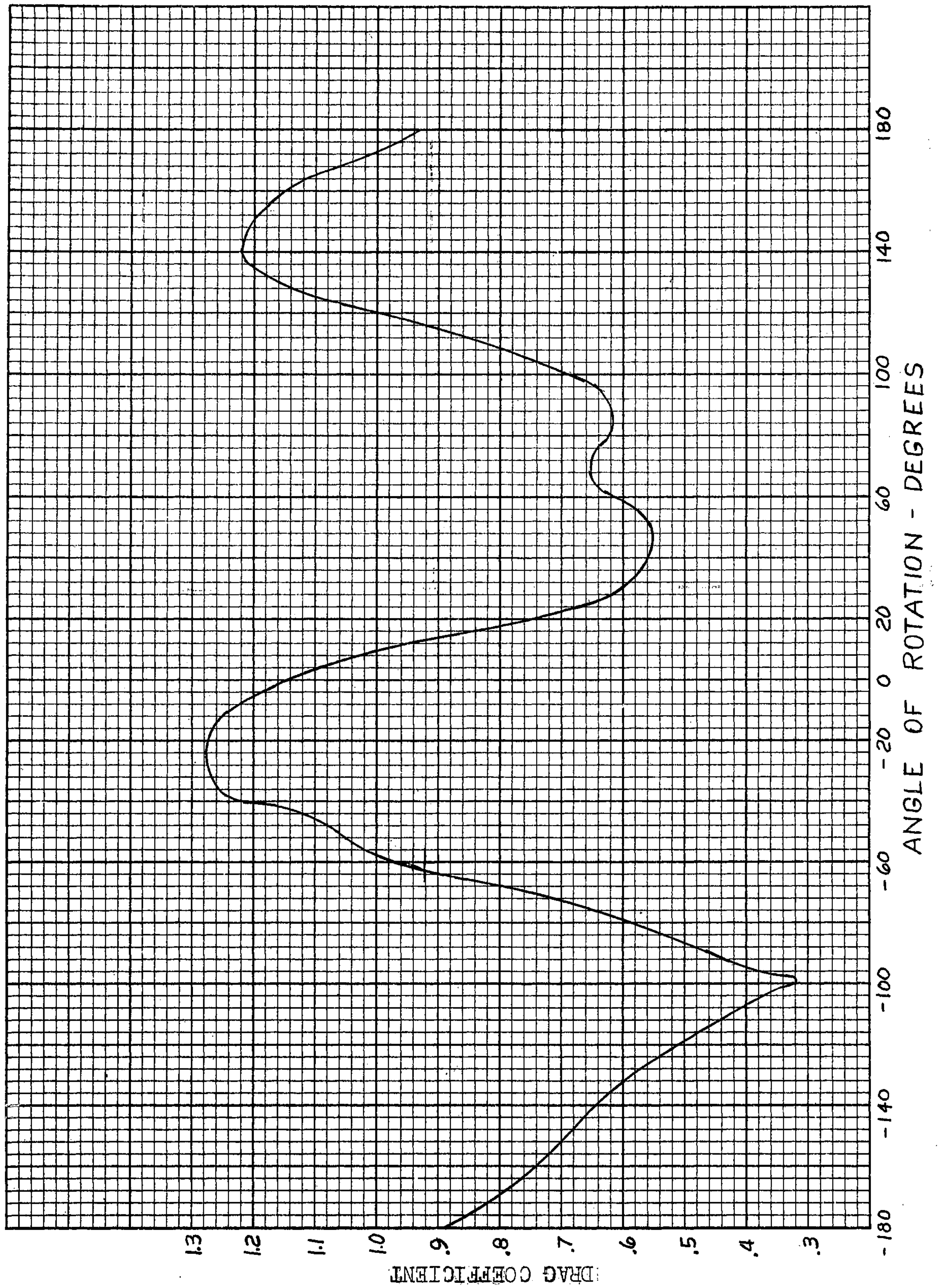

Figure No. 4

DRAG COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH .9

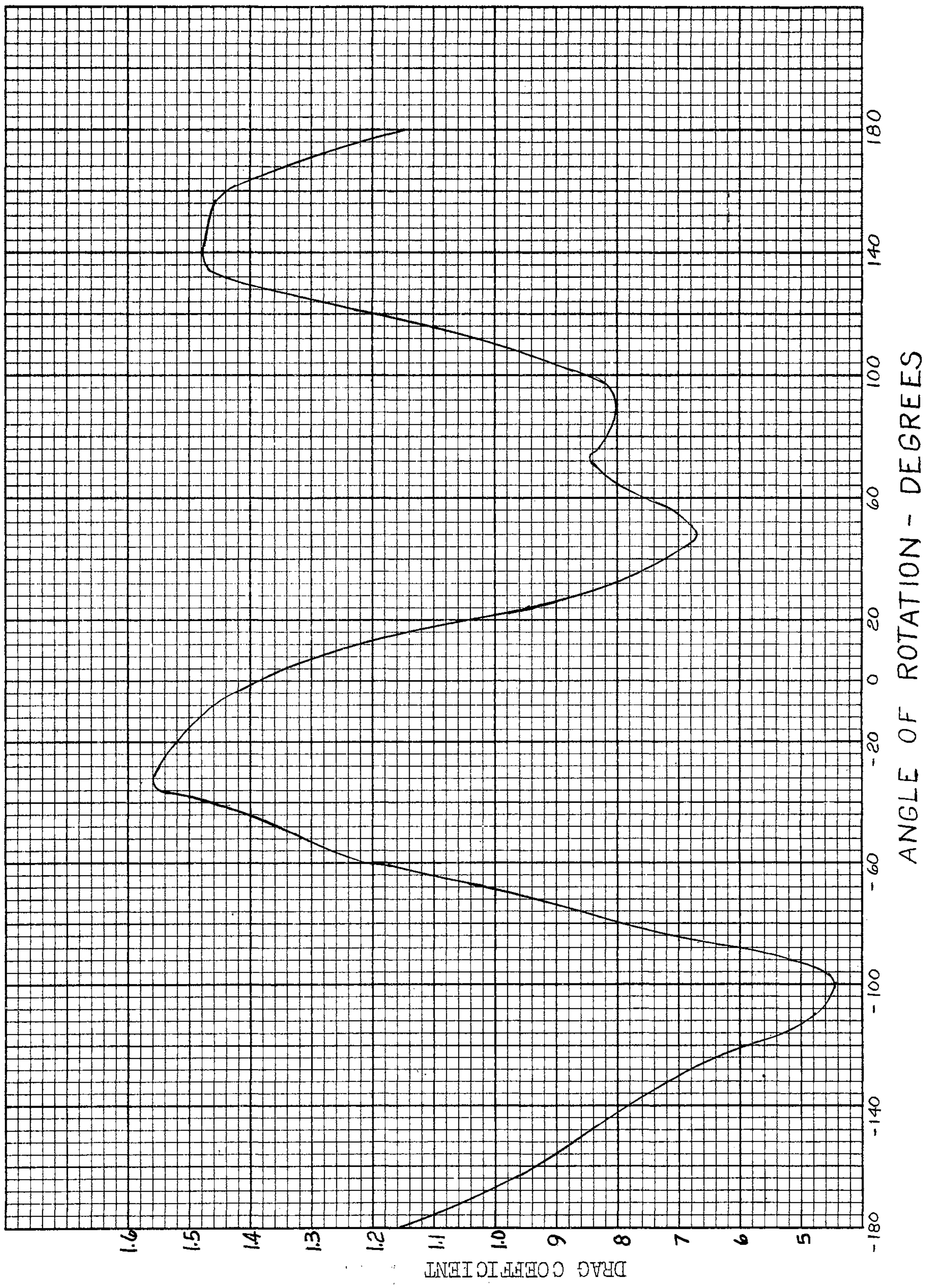

Figure No. 5

DRAG COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH 1.2

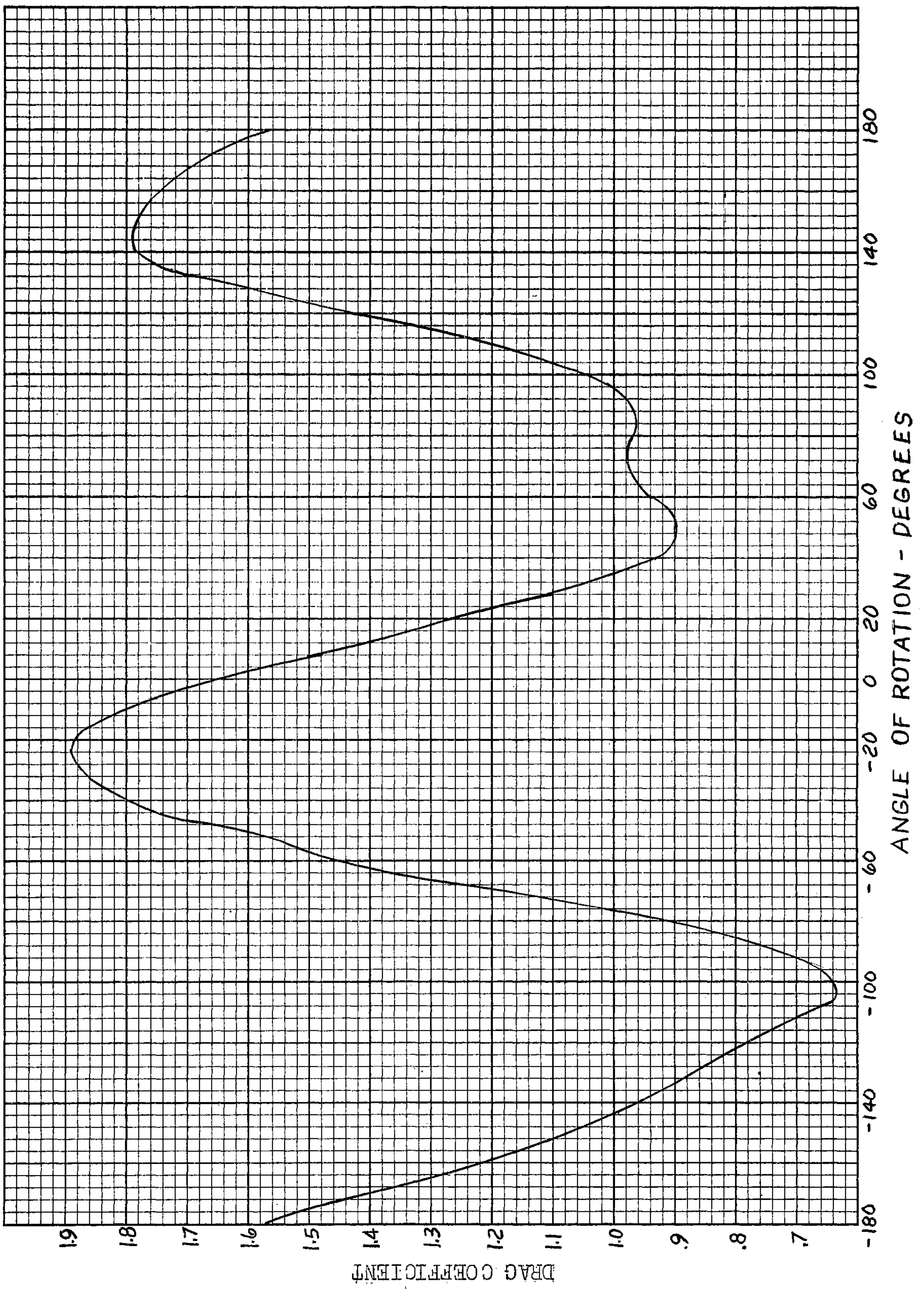

Figure No. 6

DRAG COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH 1.5

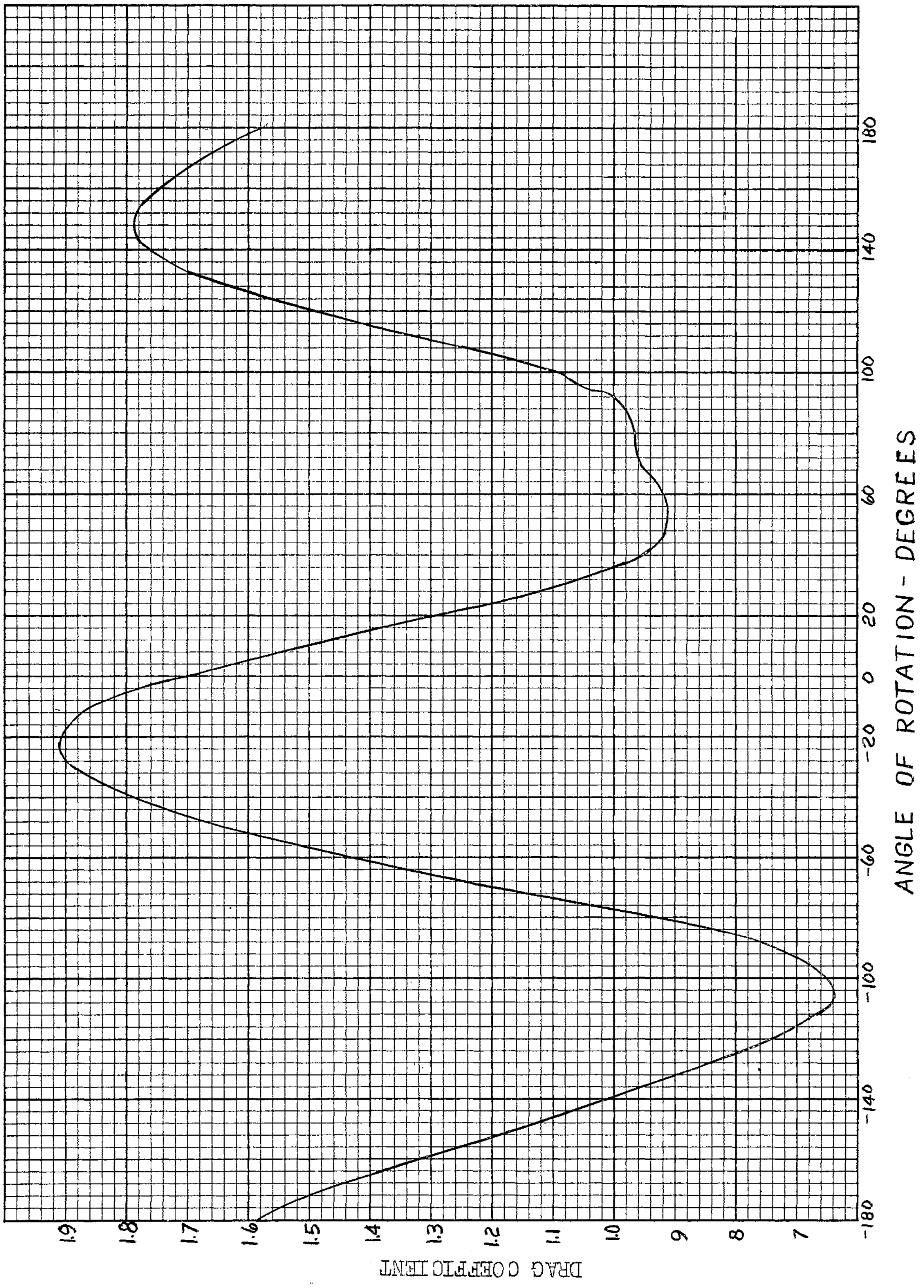

Figure No. 7

DRAG COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH 2.0

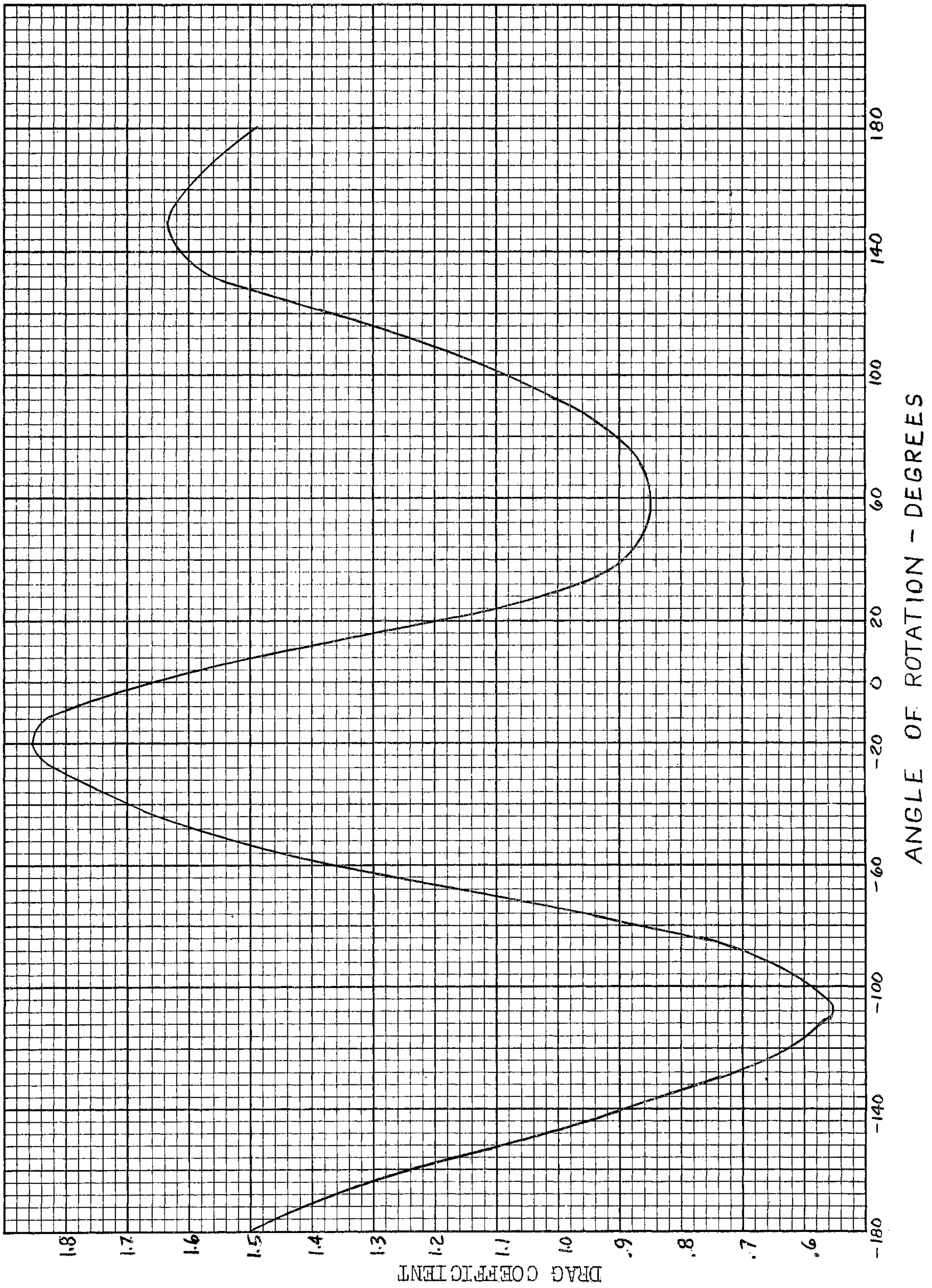

Figure No. 8

LIFT COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH .6

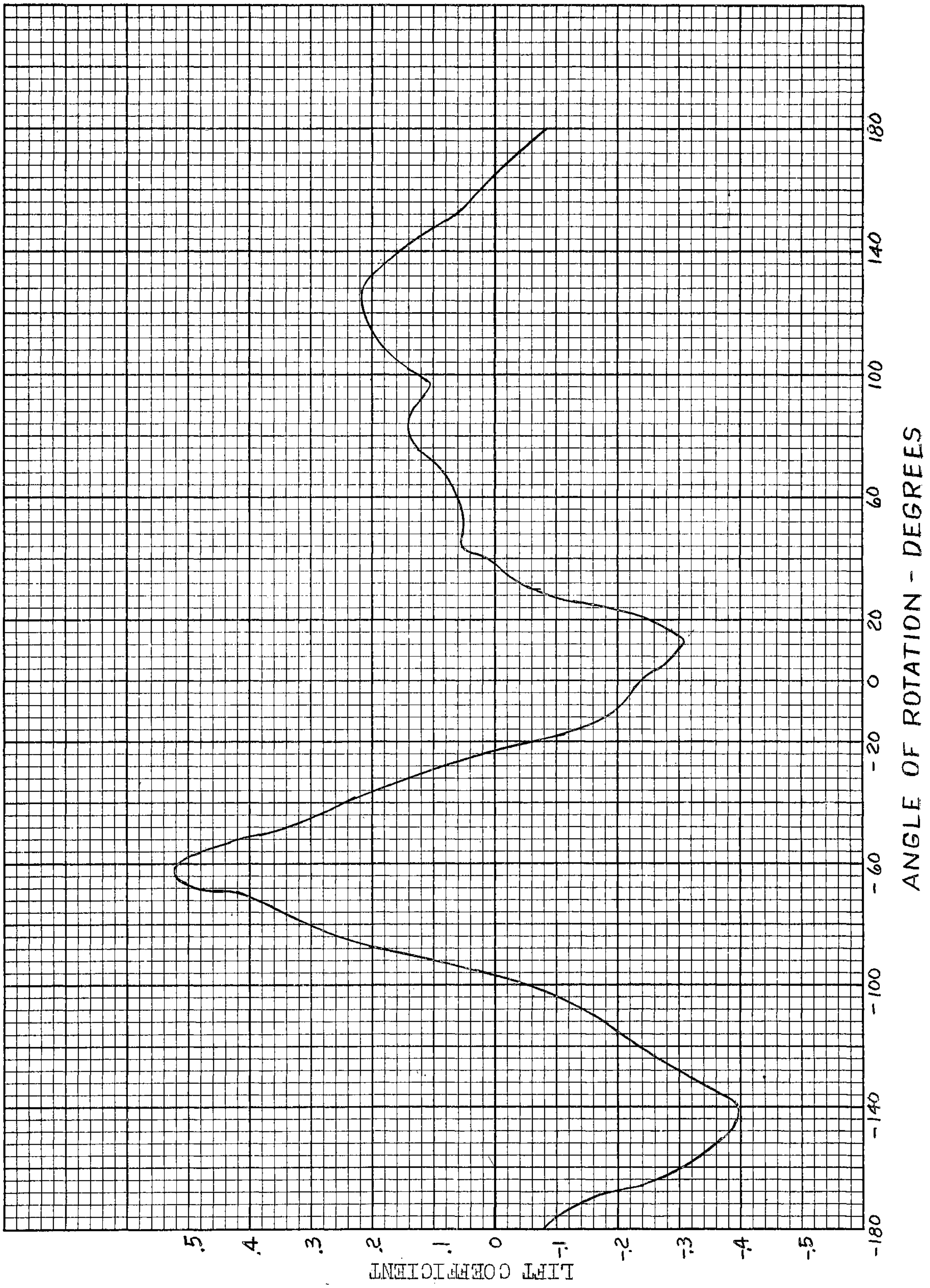

Figure No. 9

LIFT COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH .9

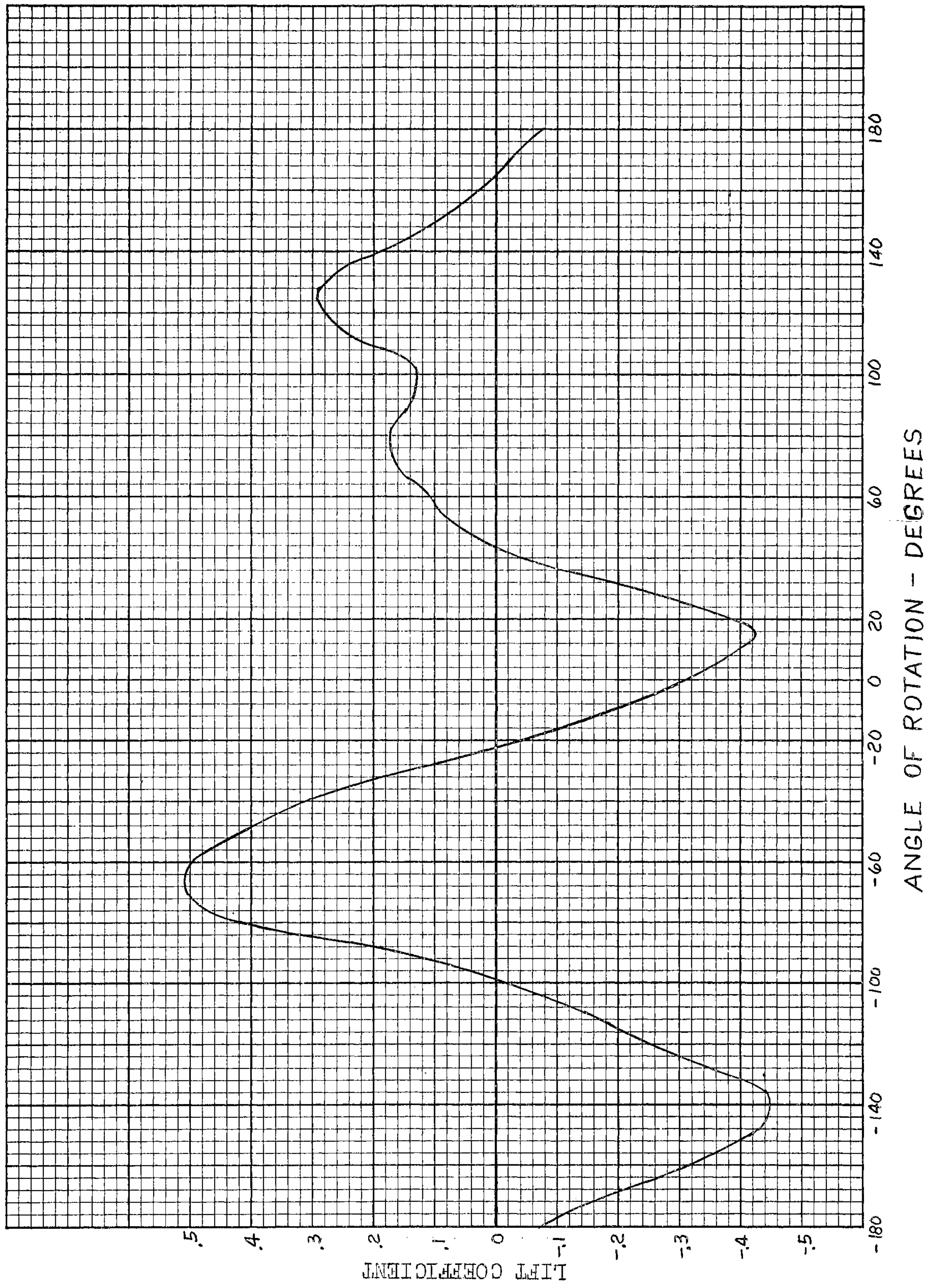

Figure No. 10

LIFT COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH 1.2

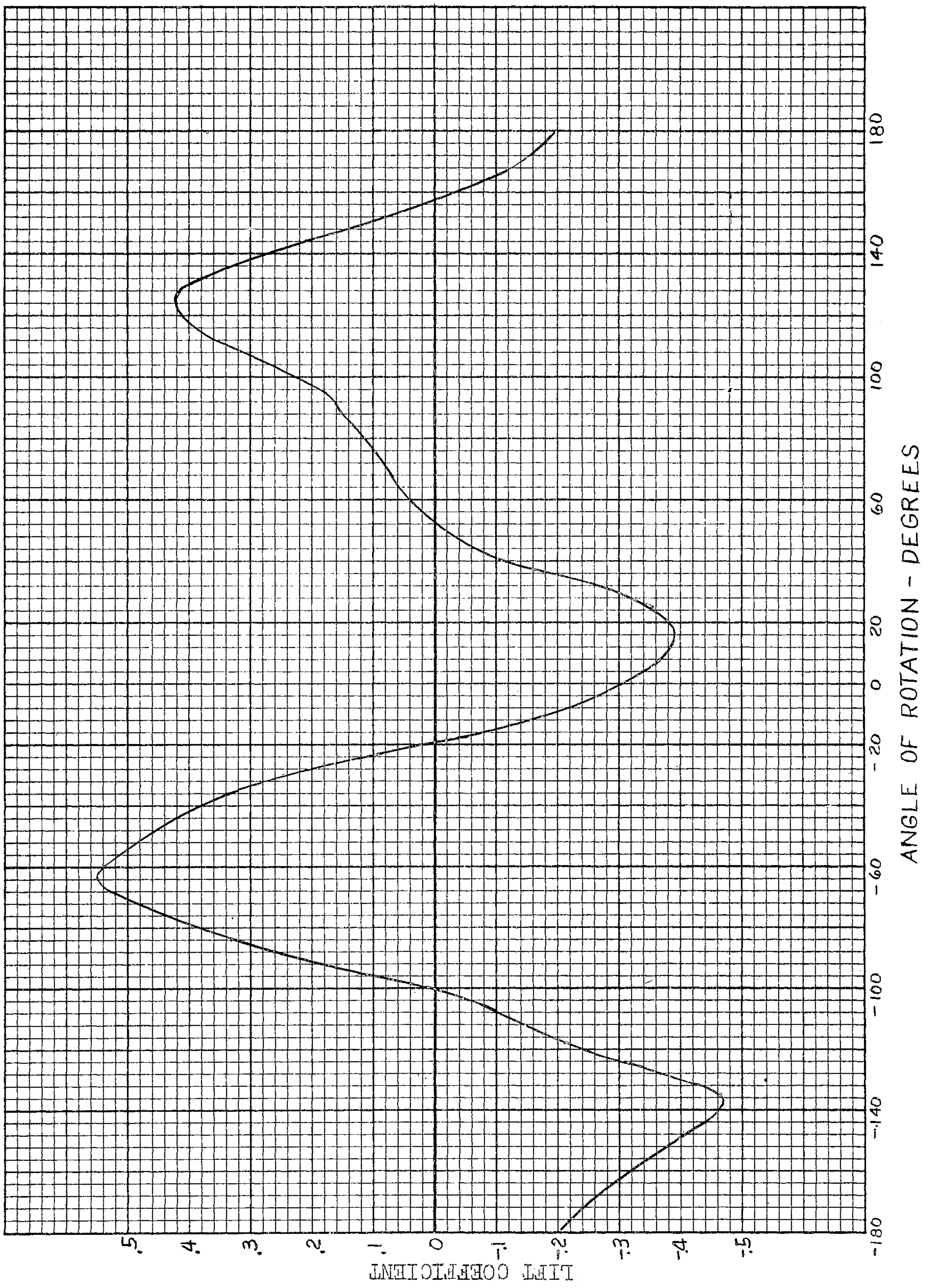

Figure No. 11

LIFT COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH 1.5

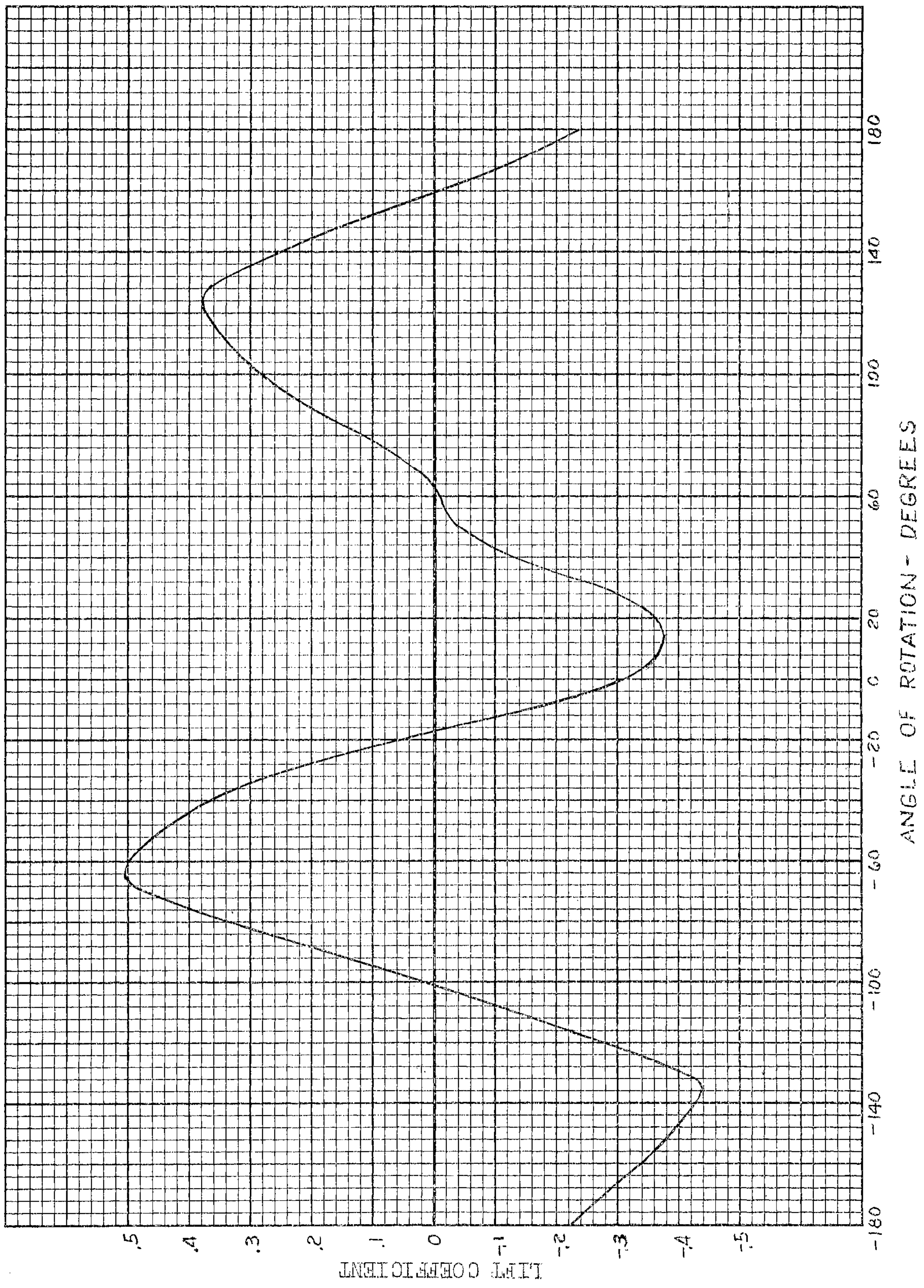

Figure No. 12

LIFT COEFFICIENT VERSUS SEAT ANGLE OF ATTACK FOR MACH 2.0

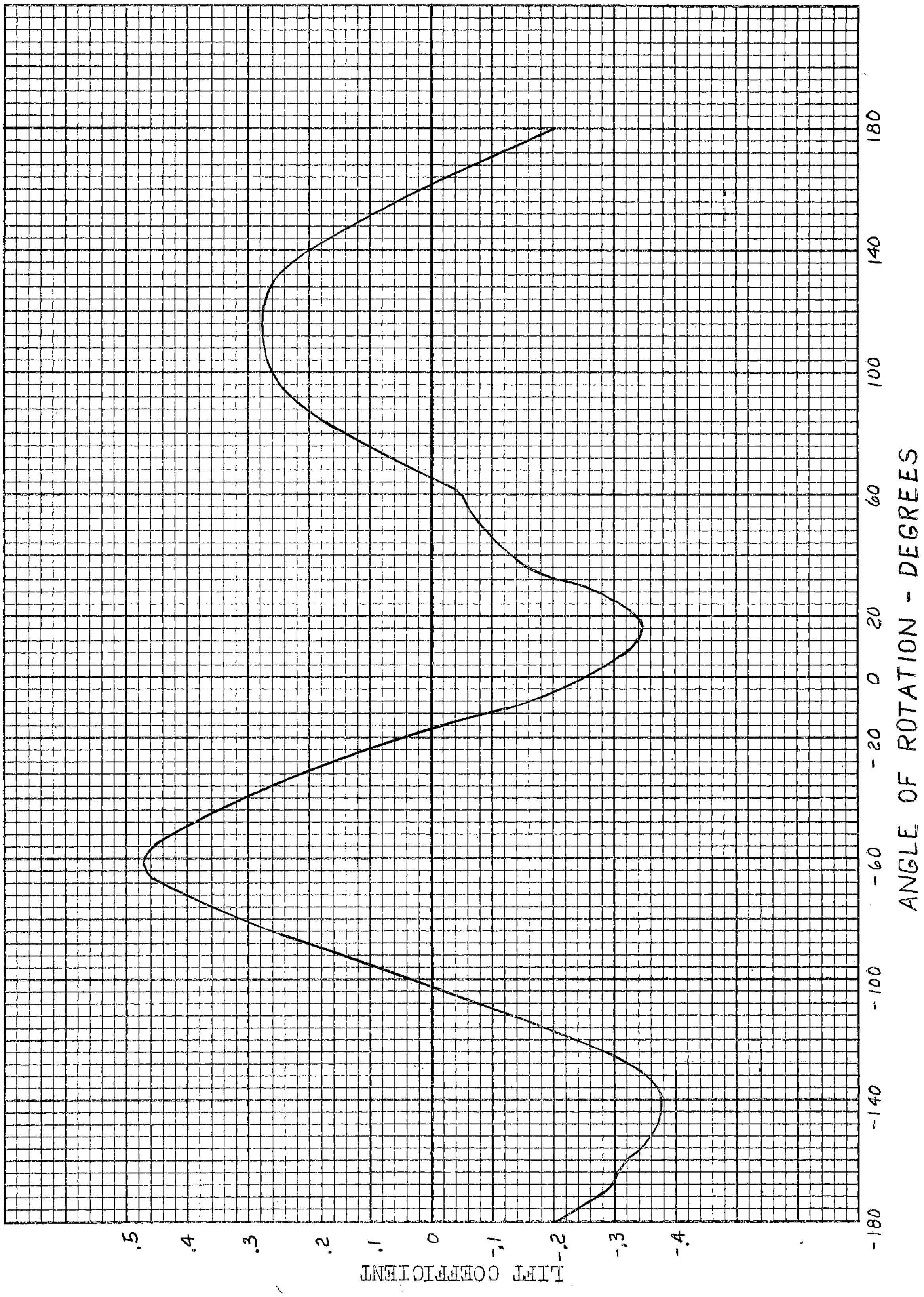

Figure No. 13

PART VI.

SAMPLE TRAJECTORY PROBLEM

In order to correlate this method with experimental trajectories, the conditions of an actual test are borrowed for the computation.

Test #2, (Reference No. 11)

Known Values:

Calibrated Indicated Airspeed $=$ 540 m.p.h.

Pressure Altitude $=$ 3000 ft.

Temperature $=$ 50° F.

Ejected Weight $=$ 287 lb.

Ejection Angle $= +13^\circ$

$\rho = .002176$ slugs/cu. ft.

$S = 5$ sq. ft.

Catapult Terminal Velocity $=$ 60'/sec.

Assumptions:

Angular Rotation $=$ 600°/sec.

Average C_D (to be used in Equation 4) $= 1.0$

Calculations:

$U_{xo} = 782 - 60 (\sin 13^\circ) = 768.5'/\text{sec.}$

$V_{yo} = 60 (\cos 13^\circ) = 58.5'/\text{sec.}$

$m = \frac{287}{32.2} = 8.92$

$$U_x = \frac{U_{xo}}{\frac{D_o\ t}{U_{xo}\ m} + 1} = \frac{U_{xo}}{\frac{C_D\ \rho\ U_{xo}\ S\ t}{2m} + 1}$$

$$U_x = \frac{768.5}{\frac{(1)\ (.002176)\ (768.5)\ (5)\ t}{2\ (8.92)} + 1} = \frac{768.5}{.469\ t + 1}$$

The following method of solution is suggested and the numerical values are shown in the table of Figure No. 14.

Steps:

1. Velocity U_x is calculated from Equation 4 at the end of each time increment.

2. The average velocity during the time increment is used to determine the average Mach number during the time increment.

3. With this Mach number and the angular position of the seat, the appropriate graphs of Figures No. 4 through No. 13 may be used to determine the average drag and lift coefficients for any specific increment of time.

4. The drag and lift forces may now be calculated.

5. Equation 5 is numerically integrated to find the velocity of the seat at the end of each time increment.

6. This velocity is in turn used in Equation 6 to find the displacement in the horizontal direction by numerical integration.

7. Equation 7 is now numerically integrated to find the vertical velocity of the seat at the end of each time increment.

8. This velocity is used in Equation 8 and by numerical integration, the displacement in the vertical direction is found.

Comparison between the actual and theoretical curves is shown in Figure No. 15.

t	U_x	U_x(Avg)	Mach No.	α	C_D	C_L	D	L	$\frac{D}{m}\Delta t$	V_x
0	768.5			+13°						13.5
		760.3	.69		1.18	-.24	3710	-755	20.8	
.05	752			-17°						34.3
		743.5	.673		1.27	+.11	3820	+331	21.4	
.10	735			-47°						55.7
		731.5	.662		.93	+.43	2705	+1250	15.2	
.15	728			-77°						70.9
		715.5	.648		.47	+.14	1310	+390	7.3	
.20	703			-107°						78.2
		695.5	.63		.51	-.25	1343	-658	7.5	
.25	688			-137°						85.7
		681	.617		.71	-.33	1790	-833	10.0	
.30	674			-167°						95.7
		668	.607		.98	-.11	2380	-268	13.3	
.35	662			-197°						109.0
		655	.594		1.2	+.11	2800	+257	15.7	
.40	648			-227°						124.7
		641.5	.58		.93	+.20	2080	+446	11.7	
.45	635			-257°						136.4
		629	.57		.64	+.12	1383	+259	7.8	
.50	623			-287°						144.2
		617.5	.56		.6	+.12	1247	+250	7.0	
.55	612			-317°						151.2
		606	.549		.7	+.11	1400	+220	7.9	
.60	600			-347°						159.1
		594.5	.538		1.08	-.12	2080	-231	11.7	
.65	589			-377°						170.8
		583.5	.528		1.15	-.21	2130	-389	11.9	
.70	578			-407°						182.7

Figure No. 14

t	$\frac{D}{2m}\Delta t^2$	$V_{xo}\Delta t$	x	$\frac{L}{m}\Delta t$	$g\Delta t$	V_{yo}	$\frac{D}{2m}\Delta t^2$	$\frac{g}{2}\Delta t^2$	$V_{yo}\Delta t$	y
0			0			58.5				0
	.52	.67		-4.23	-1.61		-.11	-.04	2.92	
.05			1.19			52.66				2.17
	.54	1.72		+1.85	-1.61		+.05	-.04	2.63	
.10			3.45			52.9				5.41
	.38	2.78		+7.00	-1.61		+.18	-.04	2.64	
.15			6.61			58.19				8.19
	.18	3.54		+2.18	-1.61		+.05	-.04	2.91	
.20			10.33			58.67				11.12
	.19	3.9		-3.69	-1.61		-.09	-.04	2.93	
.25			14.42			53.46				13.19
	.25	4.28		-4.67	-1.61		-.12	-.04	2.67	
.30			18.95			47.81				16.42
	.33	4.78		-1.5	-1.61		-.04	-.04	2.39	
.35			24.06			44.07				18.73
	.39	5.45		+1.44	-1.61		+.04	-.04	2.20	
.40			29.90			43.9				20.93
	.29	6.23		+2.50	-1.61		+.06	-.04	2.19	
.45			36.42			44.79				23.14
	.20	6.82		+1.45	-1.61		+.04	-.04	2.24	
.50			43.44			44.63				25.38
	.17	7.21		+1.40	-1.61		+.03	-.04	2.23	
.55			50.82			44.42				27.60
	.20	7.56		+1.23	-1.61		+.03	-.04	2.22	
.60			58.58			44.08				29.81
	.29	7.96		-1.29	-1.61		-.03	-.04	2.20	
.65			66.83			41.18				31.31
	.3	8.54		-2.18	-1.61		-.05	-.04	2.06	
.70			75.67			37.39				33.28

Figure No. 14 (Cont.)

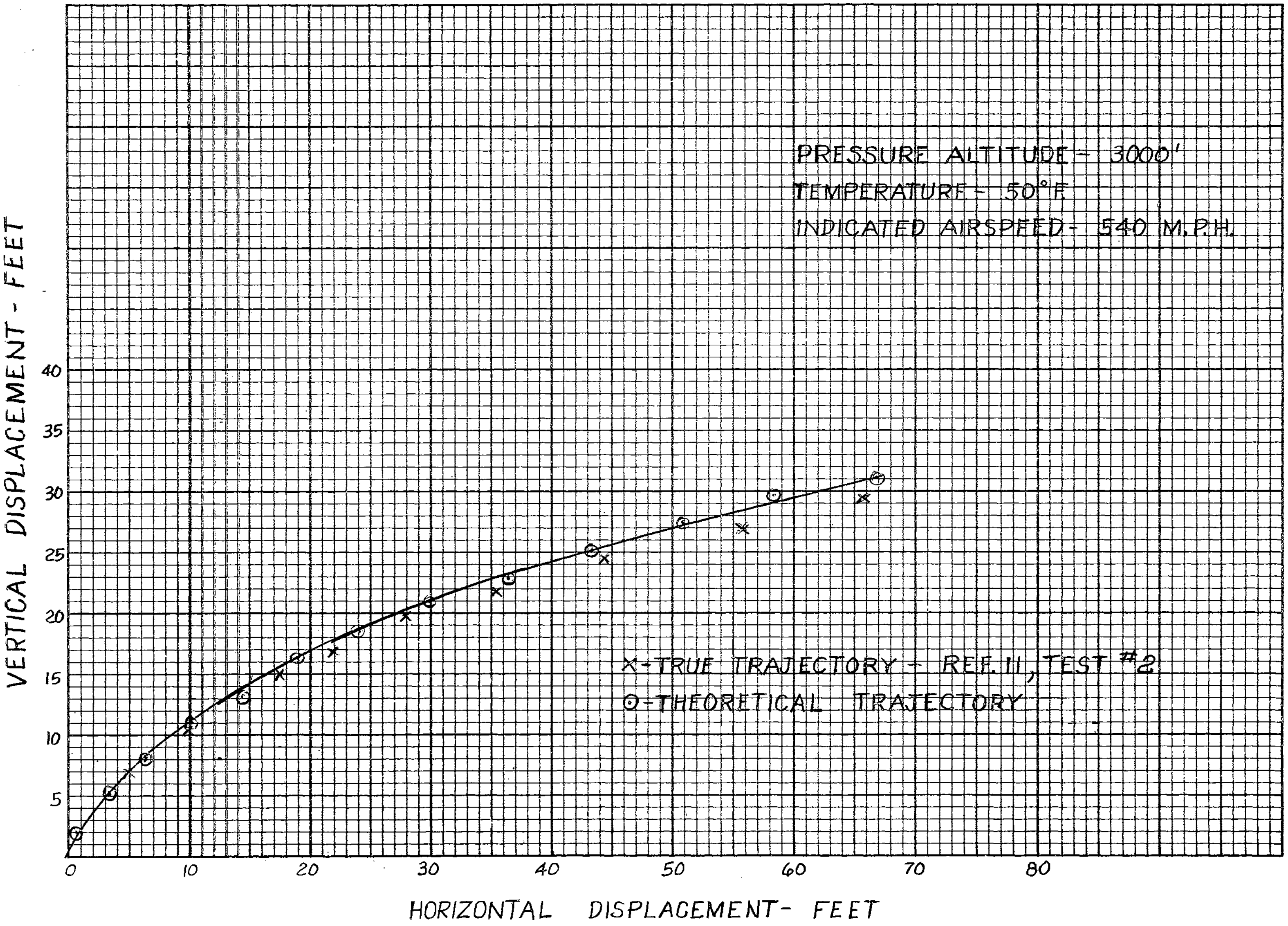
PRESSURE ALTITUDE - 3000'
TEMPERATURE - 50° F
INDICATED AIRSPEED - 540 M.P.H.
X - TRUE TRAJECTORY - REF. 11, TEST #2
⊙ - THEORETICAL TRAJECTORY
VERTICAL DISPLACEMENT - FEET
40
35
30
25
20
15
10
5
0
10
20
30
40
50
60
70
80
HORIZONTAL DISPLACEMENT - FEET

Figure No. 15

This method of solution is quite straightforward and is comparatively short. However, there is a possible pitfall during the solution which should be observed closely. The figures in Column 11 (V_X) should be checked for rather close agreement to the figures in Column 2 (U_X). This is done by subtracting the value of V_X from the initial velocity of the airplane at the time of ejection. Some discrepancies in these two values are unavoidable but if the discrepancy becomes rather large in the first few time increments, it is suggested that the values of V_X in Column 11 be used to calculate new values of U_X in Column 2 and the procedures started over again from that point.

PART VII.

CONCLUSIONS AND RECOMMENDATIONS

This report has discussed the dynamic forces acting on an upward ejection seat during the early part of the trajectory path. The importance of these forces on the trajectory curve was accepted since the justification for including them in a theoretical solution of the trajectory curve has been established by numerous tests.

Theoretical solutions of the trajectory curve may be grouped into two categories: one an exact method by means of continuous equations, and the second, a step-by-step method by utilizing numerical integration. When incorporating the dynamic forces previously mentioned into an exact continuous equation, it is found that the only practical way to arrive at the answer is by making use of an electronic computer. In the second method it is comparatively simple to adjust a solution to incorporate the dynamic forces and arrive at the answer in a short time.

The method which is developed in this report does incorporate the variables and produces results which agree well with experimental data. This method is applicable in the range of airplane speeds at which ejection seats may feasibly be used as means of escape.

Because of the circumstances under which this report was written, it was impossible to obtain a great deal of recent test data which would be helpful in demonstrating the validity of the theoretical solution given in the report. It is recommended that this method of solution be applied to up-to-date flight tests when they become available.

It is further recommended that a method to predict the rate of rotation of the seat in the airstream be developed. Included in Reference No. 14 are curves similar to Figures No. 4 through No. 13 showing the change in the moment coefficient at different Mach numbers with the change of seat angle of attack. With such curves, the method of this report may be adapted to the solution of the rotation problem.

Downward ejection seats are becoming widely used in many types of airplanes today. At this time it appears that the trajectory curves for this type seat may be solved in a similar manner as was presented in this report for upward seats. Some modification of the equations would be necessary.

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Scope of Study: A comparatively simple and economical solution of the trajectory curve of an upward ejection seat ejected from high speed aircraft is developed. A sample calculation is made to demonstrate the applicability and accuracy of the method.

Defining the forces which contribute to the motion of the seat during the trajectory was accomplished by the study of several Air Force and proprietary test reports. The forces are expressed and arranged in a manner in which they can be utilized in the proposed solution of the trajectory. These forces are made compatible with the trajectory formulas through the medium of wind tunnel test results from the Massachusetts Institute of Technology.

Findings and Conclusions: The step-by-step method of solution, as presented, is quite flexible and is more accurate than other approximating methods. It is satisfactory for the upward seat ejection units and can be easily modified for downward ejection. It also shows promise of application to jettisonable capsules.

ADVISER'S APPROVAL ______________________________